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DEVELOPMENT OF FUEL WEAR TESTS USING THE CAMERON-PLINT HIGH-FREQUENCY RECIPROCATING MACHINE

INTERIM REPORT
BFLRF No. 262

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The objectives of this program were to develop laboratory bench fuel-wear test methodology using JP-8 and to evaluate the effects of additives to improve load-carrying capacity of JP-8 for use in diesel-powered ground equipment.

A laboratory test using the Cameron-Plint High-Frequency Reciprocating machine evaluated the effects of various chemical and physical parameters influencing the lubricity of the distillate fuels. The test conditions were determined sufficient to eliminate the effect of fluid physical properties such as viscosity. It was shown that the differences in the intrinsic lubricity of the fuels were due to small amounts of chemical additives. Under such conditions, the test can be used as a screening tool to find additives for enhancement of JP-8 lubricity. The test has potential to ascertain minimum lubricity level for diesel-powered ground equipment if these requirements are verified with field performance data and determined to be different from the Air Force JP-8 specifications.

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19. **Abstract**

The dimensionless wear coefficients of Reference No. 2 diesel fuel were shown to be an order of magnitude lower than the jet fuels. In all cases, the wear rates of jet fuels and isoparaffinic solvents were improved by addition of a corrosion inhibitor or antiwear additive to match the lower wear rates of the diesel fuels. Although there was no measurable change in the viscosities of the jet fuel due to additives, the wear rates changed by an order of magnitude.

EXECUTIVE SUMMARY

Problems and Objectives: The field validation of JP-8 in diesel ground power equipment has raised concerns by propulsion system proponents and equipment/component suppliers about adequate wear life of the various fuel system components. The causes for such concerns were observed **only** in laboratory dynamometer engine tests and in full-scale pump bench tests; there has been **no** field confirmation of these laboratory-observed concerns. The objectives of this program were to develop laboratory bench fuel-wear test methodology using JP-8 and to evaluate the effect of additives to improve load-carrying capacity of JP-8.

Importance of Project: The fuel system components of diesel engines are designed for use with diesel fuels. Diesel fuels have higher viscosity than JP-8 and contain higher concentrations of naturally occurring lubricity components than JP-8. If year-around use of JP-8 in diesel-powered ground equipment verifies a JP-8 wear-related field problem, fuel lubricity screening procedures with sufficient severity to ensure adequate wear protection in diesel engine fuel system components will be required.

Technical Approach: The approach was to develop a laboratory method that could distinguish the differences in the lubricity of low-viscosity fuels and then use the determined method to evaluate the effect of additives in the fuels to reduce wear.

Accomplishments: A laboratory test machine (Cameron-Plint High-Frequency Reciprocating machine) was used to evaluate the effects of various chemical and physical parameters influencing the lubricity of the distillate fuels. The tests were conducted in the mixed boundary lubrication regime with a minimum hydrodynamic lift to show the differences in the intrinsic lubricity of the fuels due to small amounts of chemical additives. It was found that the lubricity in low-viscosity fuels is due to low concentrations of polar components and oxygenated compounds that form a load-bearing film on rubbing metal surfaces.

The dimensionless wear coefficients of Reference No. 2 diesel fuel were determined to be an order of magnitude lower than the jet fuels and isoparaffinic solvents. However, a small concentration of corrosion inhibitor or antiwear additive reduced the wear rates of the jet fuels by an order of magnitude to match the low wear rates of the diesel fuels. There was no measurable change in the viscosities of the fuels due to the additives, while the wear rates changed by an order of magnitude. The wear rates were also generally lower at higher temperatures within the temperature range of 25° to 75°C.

Military Impact: If such a future need presents itself, the methods identified in this program with additional development will result in screening procedure(s) for ensuring adequate wear life of diesel engine fuel system components using JP-8 turbine fuel.

FOREWORD/ACKNOWLEDGMENTS

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The authors acknowledge the technical assistance provided by Southwest Research Institute personnel in conducting this work. Mr. J.J. Dozier performed the experiments with the Cameron-Plint High-Frequency Reciprocating machine. The authors also acknowledge the editorial assistance provided by Mr. J.W. Pryor and Ms. S.J. Douvry in the preparation of the report.

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I. INTRODUCTION AND BACKGROUND

The field validation of MIL-T-83133 aviation turbine fuel grade JP-8 (1)* has raised concerns by propulsion system proponents and equipment/component suppliers about adequate wear life of the various fuel system components used in diesel-powered ground equipment. Such causes for concern have been observed in laboratory dynamometer (2) and full-scale bench tests (3) with fuel injection components; there has been **no** field confirmation of these laboratory-observed concerns. Dilinoleic acid (DLA) is assumed to be the active ingredient in many of the corrosion inhibitors approved for JP-8. There is clear evidence in the literature that the corrosion inhibitor also enhances the lubricity of fuel.(4) Therefore, JP-8/NATO Code F-34, which requires use of corrosion-inhibitor additive, has better lubricity than comparable Jet A-1/NATO Code F-35 that does not contain a corrosion inhibitor additive. The laboratory tests (2,4) have also shown that under extreme conditions, higher wear rates are usually obtained using JP-8 compared to Reference No. 2 diesel fuel.

The fuel pump and injector components of a diesel engine operate under a variety of conditions, depending on the engine load and speed. The Stanadyne DB2 pump used in the GM 6.2L engine is described as an example. The main rotating components of the DB2 distributor pump are the driveshaft, transfer pump blades, rotor, and the mechanical governor flyweight assembly. The 6.2L engine has a maximum rated speed of 3600 rpm, and the pump operates at one-half the crankshaft speed. The drive end of the DB2 rotor incorporates two pumping plungers. These plungers are moved towards each other simultaneously by internal cam ring lobes through rollers and shoes contained in the rotor head slots. A positive displacement vane-type transfer pump produces control pressure for plunger charging and automatic advance motion.

Thus there is a variety of geometric conditions, including high-speed rolling (cam-rollers), sliding (roller-shoe, vane blades on eccentric liner, governor weights on washer, rotor shaft, etc.), and high-speed reciprocating motion (plungers and cam roller shoes and vanes). The cam-roller and plunger have a stroke of 2 mm, and oscillations range from 240 Hz at the maximum engine speed to 50 Hz at the idle.

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*Underscored numbers in parentheses refer to references at the end of this report.

The maximum sliding velocities range from 470 cm/sec for rollers to 300 cm/sec for transfer pump vane, to 100 cm/sec for the plungers. The loads and contact pressures change during each cycle and with engine operating conditions. The maximum fuel injection pressures are 3600 psi, and roller shoe load is 240 pounds (1068 Newtons).

The "normal" wear life of various elements in such a system is that length of time acceptable in the field use with the diesel fuels. The short-term use of JP-8 in the field has not resulted in any abnormal wear leading to catastrophic failures of the fuel pumps.(5) In the short-term, field use wear rates with the JP-8 fuel may be higher than with the DF-2, but still be within the durability criteria for the fuel pump and the injection system. However, when the long-term field use JP-8 data for the fuel system wear-life become available (6,7), the wear rate data compiled in this report will be valuable if defining the screening criteria for the lubricity of the JP-8 fuel is required.

The first line of defense on wear reduction in the sliding components is the hydrodynamic fluid film. This film is primarily dependent upon the viscosity of the lubricant and kinematics of the contact. High speeds and light loadings certainly help with low-viscosity fluids such as diesel (3 cSt at 40°C) and aviation (1 to 1.5 cSt at 40°C) fuels. The end-use viscosities of each fuel may be considerably different because of the wide range in environmental temperatures and engine-operating temperature conditions. The hydrodynamic lubrication regimes in such cases may change to mixed-hydrodynamic-elastohydrodynamic (EHD, high speeds) or mixed hydrodynamic-boundary (at low speeds and high loads). In such cases, the ability of the fuel to form a pressure-induced protective film in the contact region determines the wear rates.

The boundary conditions are the most severe for promoting wear in the low-viscosity liquids. The fuel chemistry, reactivity, metallurgy, surface finish, load, and speed affect the wear. The modes of wear under boundary conditions are adhesive, corrosive, fatigue, or abrasive. The corrosive and adhesive wear modes are probably more important modes for boundary lubrication with fuels.

II. OBJECTIVE

The objective of this program was to develop laboratory bench fuel-wear test methodology and determine which additives, if any, that are required to improve the load-carrying capacity of JP-8.

III. EXPERIMENTAL APPROACH

A. Apparatus

A laboratory test Cameron-Plint High-Frequency Reciprocating (HFR) machine (8) was used in this program to evaluate the effects of various chemical and physical parameters influencing the lubricity of the distillate fuels. In the following discussion, *lubricity* is defined according to the very broad definition suggested by Appeldoorn and Dukek (9): "If two liquids have the same viscosity, and one gives lower friction, wear, or scuffing, then it is said to have better lubricity." A Cameron-Plint reciprocating machine was used to determine test conditions that sufficiently eliminated the effects of fluid physical properties such as viscosity, and to show the differences in the intrinsic lubricity of the fuels due to small amounts of chemical additives. Under such conditions, the test can be used as a screening tool to find acceptable additives to elevate the lubricity of JP-8 to the level of a referee grade diesel fuel for year-round use of JP-8 in all diesel-powered equipment.

The HFR research and development rig was used to identify test methodology that would distinguish between the small differences in the lubricity of the fuels and the effects of additives. The main useful feature of the rig is that the temperature can be easily varied and controlled from ambient temperature to 450°C. The low speeds and point contact geometry ensure low frictional heating and a negligible hydrodynamic lift. The rig also incorporates an electrical contact resistance measurement.

The apparatus is illustrated in Fig. 1. The contact configuration was ball-on-flat, and the ball was reciprocated in a horizontal plane with a pure sinusoidal motion. The scotch yoke mechanism that provides this motion was driven by a variable speed motor. The length of

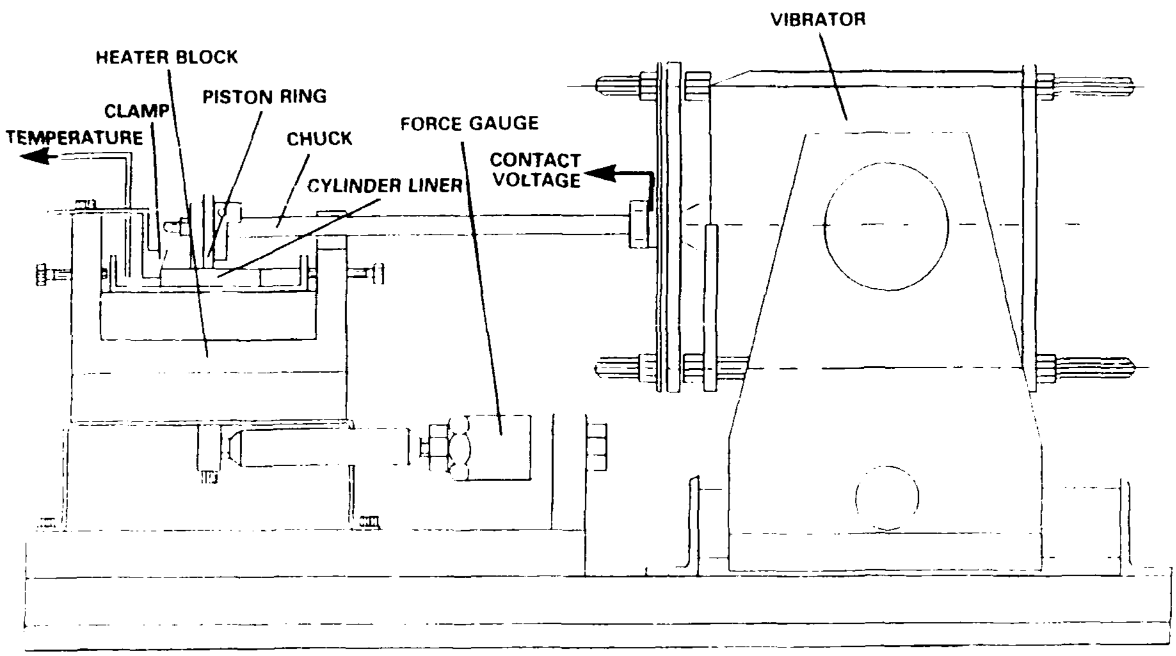

Figure 1. **<u>Schematic of the Cameron-Plint rig</u>**

the stroke could be varied from 1 to 15 mm, at frequencies ranging from 5 to 50 Hz. The fixed specimen was carried in a stainless steel bath mounted on a heater block, which was, in turn, carried on flexures. The friction force was measured by a piezoelectric transducer, and the whole assembly was vibration-isolated from the driving mechanism.The load was applied directly to the moving specimen by a spring balance. The fixed specimen can be maintained at temperatures up to 450°C by electrical resistance heaters. A close-loop controller-programmer senses the temperature of the fixed specimen by a contact thermocouple and regulates the power supply to the heaters. A wide range of temperature cycles, including heating and cooling at selected rates and isothermal temperature for any desired times, can be programmed.

B. Electrical Contact Resistance

The stationary specimen carrier is electrically insulated and the electrical contact resistance between the moving and fixed specimens is sensed by a Lunn-Furey potential divider circuit

(Fig. 2). A potential of 20 millivolts is applied across the specimens by a potential divider, and the contact resistance is observed. A reading of zero volts implies that all the voltage drop is across the contact, that is, the contact resistance is effectively zero. A 20-mV reading implies no voltage drop across the contact, and, therefore, a very large resistance (greater than 10^7 ohms).

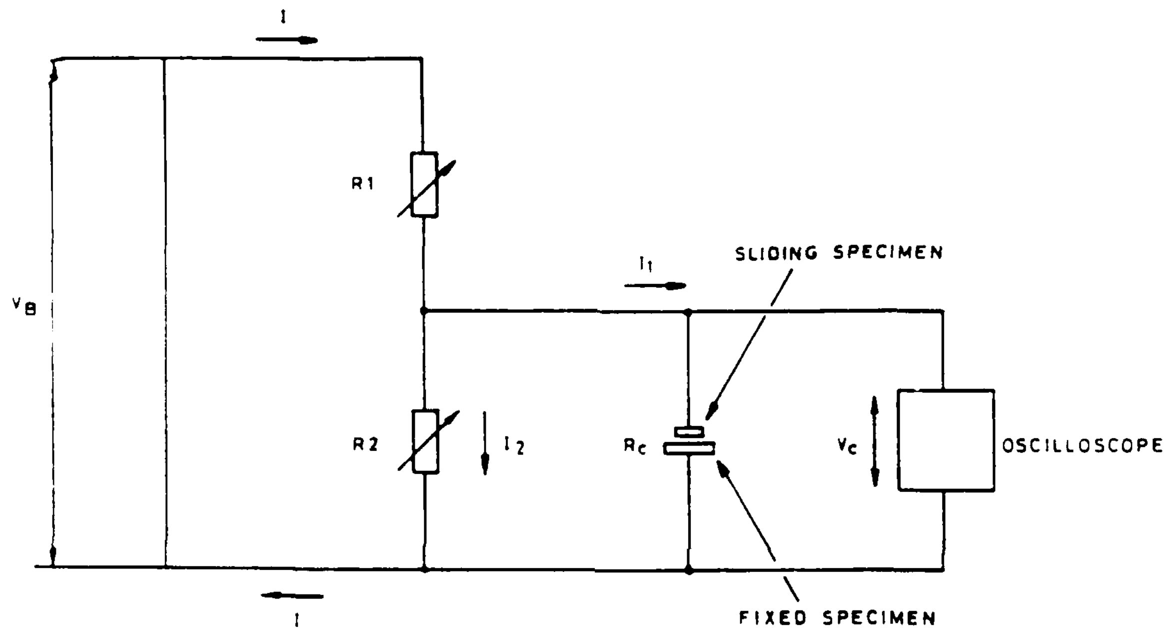

Figure 2. Lunn-Furey circuit for contact resistance measurement

C. Experimental Conditions

The test specimen for this study consisted of a 6-mm diameter ball against a static lower flat. The test specimens were fully immersed in the fuel to a depth of 2.5 mm. A positive displacement pump continuously forced a 10 mL/minute flow of fresh fuel through the bath. The ullage in the fuel reservoir was filled with nitrogen to displace any air from the reservoir.

In this study, the load was varied from 15 to 25 N, the stroke length was varied from 2.38 to 15.1 mm, and the oscillation frequency ranged from 5 to 50 Hz. The loads were large enough to produce a good friction signal and reaction film resistance when present. Most tests were conducted at isothermal temperatures of 57°C (135°F) to 74°C (165°F). Test duration for the rubbing contact varied from 1 hour to 10 hours. The repeatability of wear results with

JP-8 over a time period of 3 to 4 months was better than with the Reference No. 2 diesel fuel. However, the repeatability of results on the tests run consecutively over a period of days was considered very good with all the fuels/fluids tested.

The 6-mm diameter specimens were precision ball bearings manufactured from AISI 52100 bearing steel by Atlas Bearing Company. The flat-test specimens were AISI T-15 tungsten-type, high-speed tool steels. The flat specimens were ground and polished to 3-microinch centerline average prior to each run. The specimen surfaces were cleaned with toluene, acetone, and methanol prior to testing.

The friction and contact resistance were monitored continuously throughout the test. The friction coefficient generally ranged from 0.13 to 0.17 during the course of an experiment. The contact resistance for these polished specimens generally was zero at the start and remained very low for the duration of the test, indicating light contact density. Therefore, the wear was the most significant parameter measured for the test. The wear was measured from the scar diameter on the ball at the end of the test to an accuracy of ±0.025 mm. Wear volume was calculated for the spherical wear segment using the measured wear scar diameter and geometric formulas.

D. Test Fuels

The test fuels used in this study are described in TABLE 1. The properties for each of the three fuels are compared with the specification requirements for the respective fuel. The Reference No. 2 diesel fuel was supplied by Howell Hydrocarbons, Inc., of San Antonio, TX. The specification requirements for this fuel, commonly referred to as "Cat fuel," are set forth in section 5.2, methods 354 and 355 of Federal Test Method Standard (FTMS) 791C and described in Appendix F of ASTM STP 509A, Parts I and II.(10) This test fuel is a straight-run, mid-range natural sulfur fuel manufactured under closely controlled refinery operation to minimize batch-to-batch compositional and physical property deviations. Properties of the test fuel are given in TABLE 1 and compared with its specification requirements and the requirements of VV-F-800.(11)

The JP-8 test fuel used in these bench tests is the same fuel used in earlier endurance tests (2,3) and meets the requirements of MIL-T-83133 Aviation Turbine Fuel, JP-8.(1) This test fuel is identified as AL-14216-F, and its properties (determined at BFLRF) are given in TABLE 1. These properties are also compared to the specification requirements for MIL-T-83133/NATO F-34. Some bench tests were also conducted on an earlier batch of JP-8 identified as AL-8907-F. The properties of this fuel met specification requirements and were similar to the later fuel.

The test fuel identified as JP-8 without additives (JP-8 WOA), fuel code AL-17729-F, was procured locally and meets the specification requirements of ASTM D 1655, Aviation Turbine Fuels (12), Jet A-1. These requirements are equivalent to JP-8 fuel containing none of the requisite additives. The properties for the JP-8 WOA are also listed in TABLE 1.

In some instances, the JP-8 and JP-8 WOA test fuels were percolated through alumina prior to conduct of the wear tests. This alumina treatment, which serves to remove polar fuel constituents (and lubricity additives, if present) that enhance lubricity characteristics, was performed to obtain a "zero lubricity" fuel condition. In this manner, the effect of fuel additive additions could be separated from inherent lubricity properties.

Table 1. Properties of Reference No. 2 DF and JP-8 Test Fuels

Property	Method	Requirements		Ref. No. 2 Test Fuel (1) AL-14069-F*	MIL-T-83133C JP-8/NATO F-34		JP-8 WOA Test Fuel AL-17729-F
		Ref. No. 2 DF (1)	VV-F-800D (2)		Requirements	Test Fuel AL-14216-F	
Visual Appearance	D 4176	N/R	Clean/Bright	N/D (4)	Clean/Bright	N/D	Clean/Bright
Saybolt Color	D 156	N/R (3)	N/R	N/D	Report	+15	+30
Total Acid Number, mg, KOH/g	D 3242	N/R	N/R	N/D	0.015 max	0.005	0.012
Total Acid Number, mg/KOH/g	D 664	0.15 max	N/R	N/D	N/R	N/D	N/D
Neutralization No., mg/KOH/g	D 974	N/R	0.10 max	0.02	N/R	N/D	N/D
Aromatics, vol%	D 1319	N/R	N/R	N/D	25.0 max	19.0	25.0
Olefins, vol%	D 1319	N/R	N/R	N/D	5.0 max	0	1.9
Sulfur, Total, mass%	D 2622	0.370-0.430	0.30 max	0.41	0.3 max	N/D	<0.01
Sulfur, Total, mass%	D 4294	N/R	0.30 max	N/D	0.3 max	<0.01	N/D
Mercaptan Sulfur, mass%	D 3227	N/R	N/R	N/D	0.002 max	0.0002	<0.0001
Distillation, °C	D 86						
Initial Boiling Point		Report	N/R	206	Report	171	173
10% Recovered		Report	N/R	239	205 max	184	194
20% Recovered		N/R	N/R	N/R	Report	188	203
50% Recovered		260-270	Report	269	Report	200	222
90% Recovered		304-327	357 max	322	Report	222	260
End Point		343-366	370 max	351	300 max	238	285
Residue, vol%		N/R	3 max	1.0	1.5 max	1.0	1.0
Loss, vol%		N/R	N/R	1.0	1.5 max	1.0	0
Flash Point, °C	D 56	N/R	N/R	N/D	N/R	N/D	58
Flash Point, °C	D 93	38 min	56 min	82	38 min	56	N/D
Gravity, API	D 1298	32-35	N/R	34.5	37-51	40.3	40.7
Density, 15°C, kg/L	D 1298	N/R	0.815-0.860	0.8520	0.755-0.840	0.8232	0.8217
Freeze Point, °C	D 2386	N/R	N/R	N/R	-47 max	-55	-51
Cloud Point, °C	D 2500	Report	-13 max	-10	N/	N/D	N/D
Pour Point, °C	D 97	-7 max	-18 max	-13	N/R	N/D	N/D
Kinematic Viscosity,	D 445						
-20°C, cSt		N/R	N/R	N/D	8.0 max	4.14	2.6
37.8°C, cSt		3.0-4.0	N/R	3.12	N/R	N/D	N/D
40°C, cSt		N/R	1.9-4.1	2.98	N/R	1.26	1.62
70°C, cSt		N/R	N/R	N/D	N/R	N/D	1.08
Hydrogen, mass%	D 3178	N/R	N/R	12.19	13.4 min	13.69	N/D
Net Heat of Combustion,	D 240						
Btu/lb		N/R	N/R	18,279	18,400 min	18,532	18,672
MJ/kg		N/R	N/R	42.516	42.8 min	43.106	43.431
Smoke Point, mm	D 1322	N/R	N/R	N/D	25.0 max or 19 min	2.2	14.0
Naphthalenes, vol%	D 1850	N/R	N/R	N/D	AND 3.0 max	N/D	0.6
Copper Corrosion	D 130						
2 hours at 100°C		N/R	N/R	N/D	1B max	1A	1A
3 hours at 50°C		2 max	1 max	1A	N/R	N/D	N/D
Thermal Stability (JFTOT)	D 3241						
Visual Code		N/R	N/R	N/D	<3 max	1	1
Change in Pressure Drop, mm Hg		N/R	N/R	N/D	25 max	0	0
Carbon Residue on 10% Bottoms, mass%	D 524	0.20 max	0.20 max	0.11	N/R	N/D	N/D
Existent Gum, mg/100 mL	D 381	N/R	N/R	N/D	7.0 max	0.2	1.6
Ash, mass%	D 482	0.01 max	0.02 max	0.01	N/R	N/D	N/D
Particulate Matter, mg/L	D 2276	N/R	10 max	N/D	1.0 max	1.1	0.1
Water and Sediment, vol%	D 1796	0.05 max	N/R	0.01	N/R	N/D	N/D
Water Reaction	D 1094						
Interface Rating		N/R	N/R	N/D	1B max	1B	1
Separation Rating		N/R	N/R	N/D	N/R	N/D	2
Water Separation Index, Microsep	D 3948	N/R	N/R	N/D	70 min	N/D	82
Cetane Number	D 613	45-51	45 min	52	N/R	41	42.3
Cetane Index	D 976-80	Report	43 min	47	N/R	N/D	N/D
Fuel System Icing Inhibitor	FED-STD-791, Method 5340	N/R	N/R	N/D	0.10-0.15	0.01, 0.04	None
Corrosion Inhibitor, g/m^3	HPLC	N/R	N/R	N/D	N/R	14 (5)	None
Fuel Electrical Conduct, pS/m	D 2624	N/R	N/R	N/D	150-600	170, 90	N/D
Filtration Time, minutes	Apdx. A	N/R	N/R	N/D	15 max	72	N/D

* Batch 85-2
(1) *ASTM STP 509A, Part I and Part II, Appendix F*
(2) Requirements for Grade DF-2 (NATO F-54)
(3) No Requirement
(4) Not Determined
(5) Fuel supplier added 14 g/m^3 of Lubrizol 541

IV. TEST RESULTS AND DISCUSSIONS

The initial tests were conducted at relatively high loads and point contact geometry. The wear results for 1-hour duration tests are summarized in TABLES 2 through 5. The rationale for developing the bench wear test was that the hydrodynamic film with the low viscosity fluids (1 to 3 cSt) is easily compromised; therefore, the inherent wear protection ability of the fuel under mixed boundary conditions is the major factor in the wear rates of the fuel components. The fuel pump and injection components in a diesel engine perform under a variety of geometric conditions, pressures, and velocities to cover lubrication conditions from the boundary to fully developed hydrodynamic film. However, the wear can occur only as a result of the boundary or EHD conditions.

The dimensionless wear coefficient, K, was calculated for various fuels and test conditions to facilitate the interpretation of the bench test results.

$$K = WH/Lvt$$

where,
- W = wear volume
- H = hardness
- L = load
- v = velocity
- t = time

TABLE 2 shows the magnitudes of the wear coefficients of various fuels/lubricants under identical test conditions.

The wear coefficients of a Reference No. 2 diesel fuel are an order of magnitude lower than the jet fuels (with or without corrosion inhibitor additive) and isoparaffinic solvents. The wear rates of 40-weight bright stock and paraffinic mineral oil, along with the viscosities, are also included in TABLE 2 for a comparison. The wear coefficient (K) of the bright stock oil is an order of magnitude lower than the diesel fuel; however, there is only a twofold decrease in K from the diesel fuel to the mineral oil.

TABLE 2. Wear Coefficients of Various Fuels/Lubricants

Fuels/Lubricants	Viscosity at 40°C, cSt	Wear Coefficient K* (Dimensionless) at 57°C	Wear Coefficient K* (Dimensionless) at 74°C
40-weight Bright Stock	144	9×10^{-9}	9×10^{-9}
Mineral Oil (Paraffinic)	68	9×10^{-8}	2×10^{-8}
Reference No. 2 Diesel Fuel	3	2×10^{-7}	4×10^{-8}
JP-8 (AL-14216-F)	1.26	1×10^{-6}	2×10^{-7}
JP-8 (AL-8907-F)	--	1×10^{-6}	7×10^{-7}
JP-8 WOA	1.6	2×10^{-6}	1×10^{-6}
Isopar-G**	1.0	1×10^{-5}	--
Isopar-M**	2.4	6×10^{-6}	--

* K = WH/Lvt; where W = wear volume, H = hardness, L = load, v = velocity; and t = time.
Average Velocities: 21.1 cm/sec Ball-on-Flat
Load: 25 N
**Products of Paramins Division LUBE TEXT DG-1P, 31 Jan 1983--These are synthetically produced isoparaffinic solvents.

TABLE 3 presents the effect of velocities on the wear coefficients of a diesel fuel and a jet fuel. There was no significant change in the wear rate in the case of the diesel fuel when the average velocities were changed from 2.4 cm/sec to 23.8 cm/sec. In the case of the JP-8 WOA fuel, the wear rates decreased slightly with the increased velocities. Thus, the effect of hydrodynamic lift and surface roughness is still inherent in the test procedure. However, the hydrodynamic effect is minimized so that the wear coefficient magnitudes are not significantly changed. In other words, the wear coefficients of JP-8 WOA fuel over the velocity range are still an order of magnitude larger than the wear coefficients of the diesel fuel.

The wear rates were generally lower at higher temperatures within the temperature range of 25° to 75°C (77° to 167°F). These rates are shown in TABLE 4 for JP-8 WOA fuel. The wear rates increased by a factor of three when the temperature was decreased from 74° to 25°C (165° to 77°F). TABLE 4 also lists the fuel viscosity as a function of temperature.

TABLE 3. Effect of Velocity on Wear Coefficient

Fuels/Lubricants	Temp, °C	Velocity, cm/s		Wear Coefficient K (Dimensionless)
		Maximum	Average	
Reference No. 2 Diesel Fuel	57	37.4	23.8	4.0×10^{-7}
Reference No. 2 Diesel Fuel	57	33.1	21.1	2.0×10^{-7}
Reference No. 2 Diesel Fuel	57	3.7	2.4	5.0×10^{-7}
JP-8 WOA, Alumina Treated	57	71.0	45.2	2.0×10^{-6}
JP-8 WOA, Alumina Treated	57	47.4	30.2	2.6×10^{-6}
JP-8 WOA, Alumina Treated	57	33.1	21.1	3.3×10^{-6}
JP-8 WOA, Alumina Treated	57	23.7	15.0	4.5×10^{-6}

TABLE 4. Effect of Temperature on Wear Coefficient

Fuel: AL-17729-F (JP-8 WOA), Alumina Treated
Sliding Velocity, cm/sec Maximum: 33.1 Average: 21.1

Temperature, °C	Viscosity, cSt	Wear Coefficient K (Dimensionless)
25	2.01	6.0×10^{-6}
40	1.62	6.0×10^{-6}
57	1.28	3.5×10^{-6}
74	1.05	2.0×10^{-6}

The fuel viscosity changes from 1 cSt at 75°C to 2 cSt at 25°C. Thus, the chemical reactivity of the fuel in providing wear protective surface film at higher temperatures more than offsets the adverse effect of reduced viscosity on the hydrodynamic lift.

TABLE 5 presents the effect of corrosion inhibitor or antiwear additives on the wear rates. In all cases, the wear rates of the jet fuels or isoparaffinic solvents are improved by an order of magnitude to match the low wear rates of the diesel fuel. There is no measurable change in the viscosities of each individual fuel due to additives, although the wear rates change by an order of magnitude.

TABLE 5. Effect of Corrosion Inhibitor/Antiwear Additives on Wear Rates

Fuels/Lubricants	Viscosity at 40°C, cSt	Wear Coefficient K* (Dimensionless) at 54°C	Wear Coefficient K* (Dimensionless) at 74°C
Reference No. 2 Diesel Fuel	3.0	2×10^{-7}	4×10^{-8}
Isopar-G*	1.0	1×10^{-5}	--
Isopar-G + 0.02 g/L DLA**	1.0	1×10^{-6}	8×10^{-7}
Isopar-G + 2.0 g/L ECA 831***	1.0	3×10^{-8}	3×10^{-8}
Isopar-M*	2.4	6×10^{-6}	--
Isopar-M + 0.02 g/L DLA	2.4	4×10^{-7}	--
Isopar-M + 2.0 g/L ECA 831	2.4	3×10^{-8}	3×10^{-8}
Isopar-M + 0.02 g/L DLA + 2.0 g/L ECA 831	2.4	3×10^{-8}	--
JP-8 (AL-8907-F)	--	1×10^{-6}	7×10^{-7}
Alumina Treated + 0.02 g/L DLA + 2 g/L ECA 831	--	3×10^{-8}	4×10^{-8}
JP-8 (Unmarked)			
Alumina Treated	1.0	2×10^{-6}	5×10^{-7}
Alumina Treated + 0.02 g/L DLA	1.0	4×10^{-7}	--
Alumina Treated + 0.02 g/l DLA + 2 g/L ECA 831	1.0	9×10^{-9}	--
JP-8 WOA (AL-17729-F)	1.6	2×10^{-6}	1×10^{-6}
Jet A + 0.02 g/L DLA	1.6	2×10^{-6}	--
Jet A + 1.0 g/L DLA	1.6	3×10^{-8}	5×10^{-8}
Jet A + 0.2 g/L ECA 831	1.6	3×10^{-7}	--
Jet A + 2.0 g/L ECA 831	1.6	3×10^{-8}	--
JP-8 WOA (Alumina Treated)	1.6	2×10^{-6}	8×10^{-7}
Alumina Treated + 0.02 g/L DLA	1.6	2×10^{-8}	--
Alumina Treated + 1 g/L ECA 831	1.6	6×10^{-8}	5×10^{-8}
Alumina Treated + 2 g/L ECA 831	1.6	3×10^{-8}	4×10^{-8}

* Products of Paramins Division.
** Corrosion Inhibitor - Dilinoleic Acid - DLA.
***Antiwear Additive - Paramins ECA 831.

Fig. 3 graphically presents the progression of the wear volumes with accumulated sliding distance. A 40-weight bright stock oil, Reference No. 2 diesel fuel, and JP-8 WOA, as well as the blends of heavier oils with the latter were used as test fluids. The tests were conducted at the slowest controllable speeds of 5 Hz and the normal load of 25 N to assure mixed boundary conditions. Examination of the wear curve for the Reference No. 2 diesel fuel shows an initial wearing-in for a sliding distance of approximately 70 meters, which is roughly equivalent to the first 15,000 cycles or 1 hour. It should be noted that the wear curves are plotted on a log-log scale. The wear rate for the next 10 hours is extremely gradual and consists essentially of polishing the wear scar area. The wear curve for 40-weight bright stock oil is very similar to that for the diesel fuel. The wear curve for JP-8 WOA shows a continuous adhesive/abrasive wear pattern that does not stabilize, and it is at least an order of magnitude higher than the wear curve for diesel fuel. Addition of 5 vol% bright stock in the jet fuel did not significantly change the wear rate or pattern. The addition of diesel fuel at 5 vol%, however, did have a beneficial effect on the wear characteristics of JP-8 WOA.

Fig. 4 presents the effect of increasing additive concentration on the wear volumes as a function of sliding distance. The test used AISI 52100 ball reciprocating at 5 Hz, 2.38-mm stroke, on a T-15 tool steel. Each curve in Fig. 4 was developed by interrupting the test at regular time intervals and measuring the wear scar diameter on the ball. The worn ball was positioned exactly in the same wear track after the scar measurement, and the test was resumed. The test was terminated at the end of 750 minutes or earlier if the wear scar diameter was larger than 0.8 mm. During the test, the specimens were continuously flushed with fresh fuel at a flow of 2 mL/min. The bulk temperature of the steel plate and fuel was isothermally maintained at either 57°C (135°F) or 74°C (165°F). In a reciprocating motion, the velocity of sliding approaches zero at the end of the stroke and then reverses the direction; therefore, both the total sliding distance as well as the number of cycles traversed are meaningful quantities. The horizontal axis in Fig. 4, therefore, has distances and the equivalent cycles scales.

Figs. 4 through 6 show the complex relationship between corrosion inhibitor (dilinoleic acid) concentration, temperature, and wear volumes as a function of sliding distance under the mixed boundary conditions of the test.

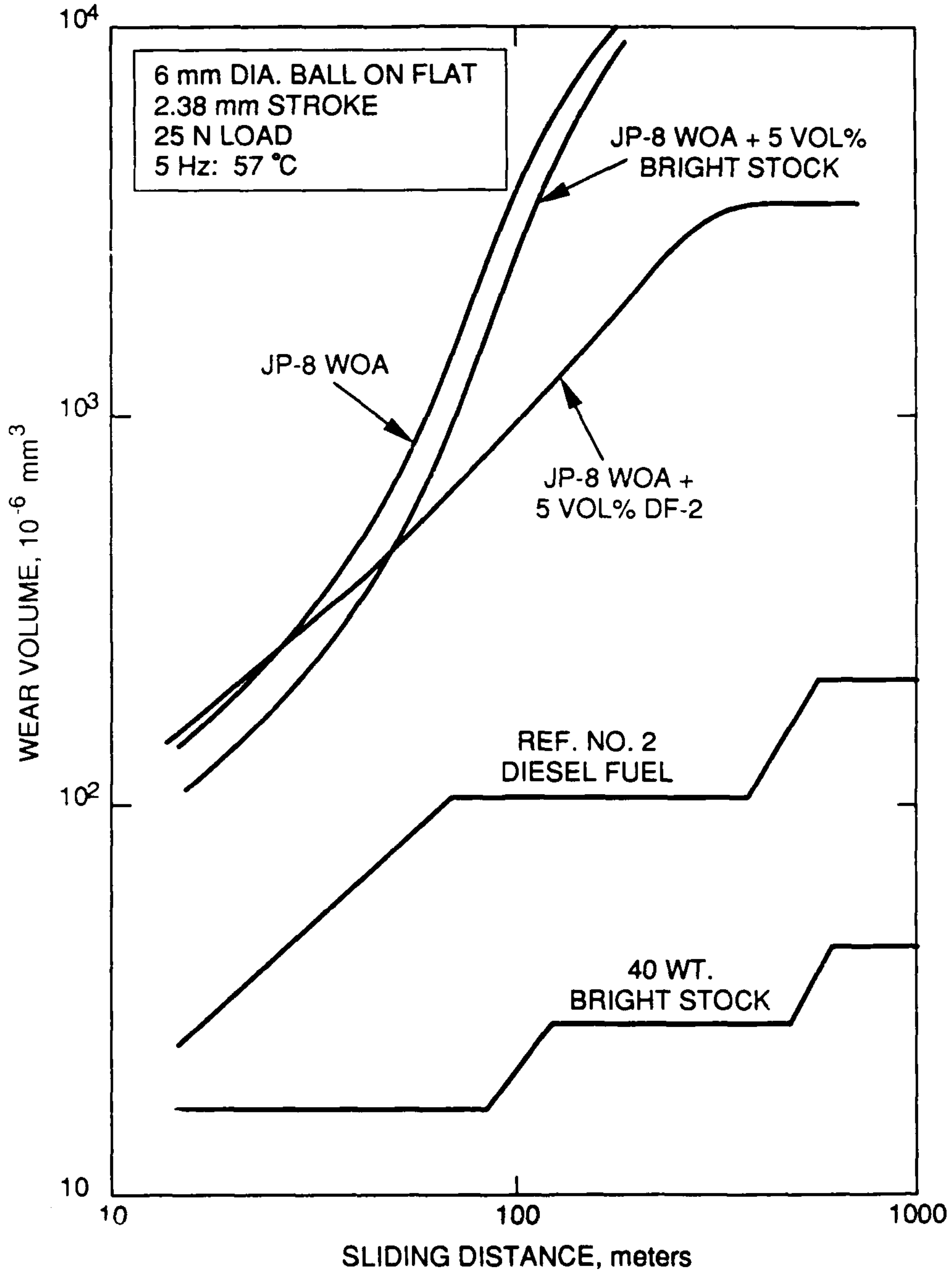

Figure 3. Wear volumes as a function of sliding distance

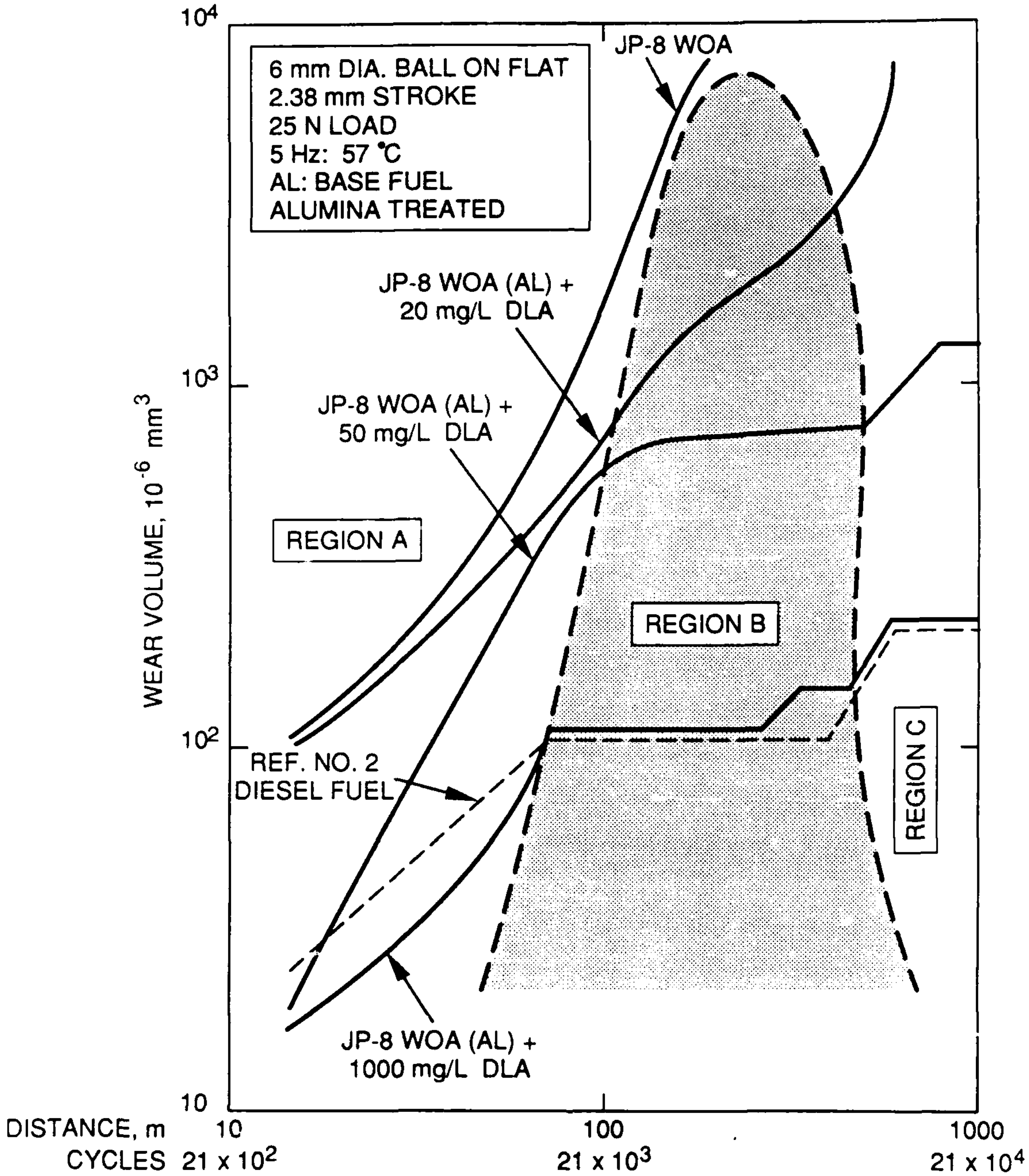

Figure 4. Effect of additive concentration on wear at 57°C

The wear curves of JP-8 WOA, and the fuel containing 20, 50, and 1000 mg/L dilinoleic acid (DLA) for 57°C (135°F) test temperature are presented in Fig. 4. The wear curve for a Reference No. 2 diesel fuel is also included in Fig. 4 for the comparison. All wear curves have three general regions of wear rates as the sliding distance or time increases. These regions are roughly bracketed in 0- to 100-m, 100- to 500-m, and beyond 500-m distances. The initial wearing is defined by Region A for the sliding distance range of 20 to 100 meters, which is roughly equivalent to 15 x 10^3 cycles or 1 hour. The wear rates are high because of small contact areas and resulting high pressures. Region B is the area indicating long duration and slow steady-state wear. Region C indicates a very high wear rate at the end due to some change in the wear mechanism.

Region B in the series of curves in Fig. 4, which range from neat JP-8 WOA to 1000 mg/L of DLA, shows the increasing effect of DLA in reducing the wear rate (slope) and extending the length of Region B. JP-8 WOA has no sharp demarcation among Regions A, B, and C, and a steep slope changes continuously and gradually. The addition of 20 mg/L of DLA distinctly changes the slope in Region B and the three regions are distinguishable. The additive concentration of 50 mg/L DLA dramatically changes the slope in Region B to almost zero and shifts the region to the left. Thus, the net effect of increasing the concentration of the additive is to reduce the wear-in time and volume in Region A, and to increase the steady-state wear life in Region B. The beneficial effect seems to continue increasing with 1000 mg/L DLA, which has a wear curve overlapping the wear curve of Reference No. 2 diesel fuel.

The effect of temperature on the wear with various concentrations of DLA in the JP-8 WOA is shown in Figs. 5 and 6. The wear curves for 10 and 20 mg/L concentration in Fig. 5 shift toward lower wear rates as the temperature increases from 57° to 74°C, i.e., the wear volumes are smaller at the higher temperature. This trend is not exactly followed at very high concentrations of 1000 mg/L. Fig. 6 shows that for the concentration of 50 mg/L, the higher temperature leads to more wear. This trend is reversed from the one for 10 and 20 mg/L curves in Fig. 5. The reasons for this behavior can be qualitatively assigned to higher additive reaction rates with the iron surfaces at increased concentrations and temperatures and the changes in the mechanisms of wear with the reaction rates.

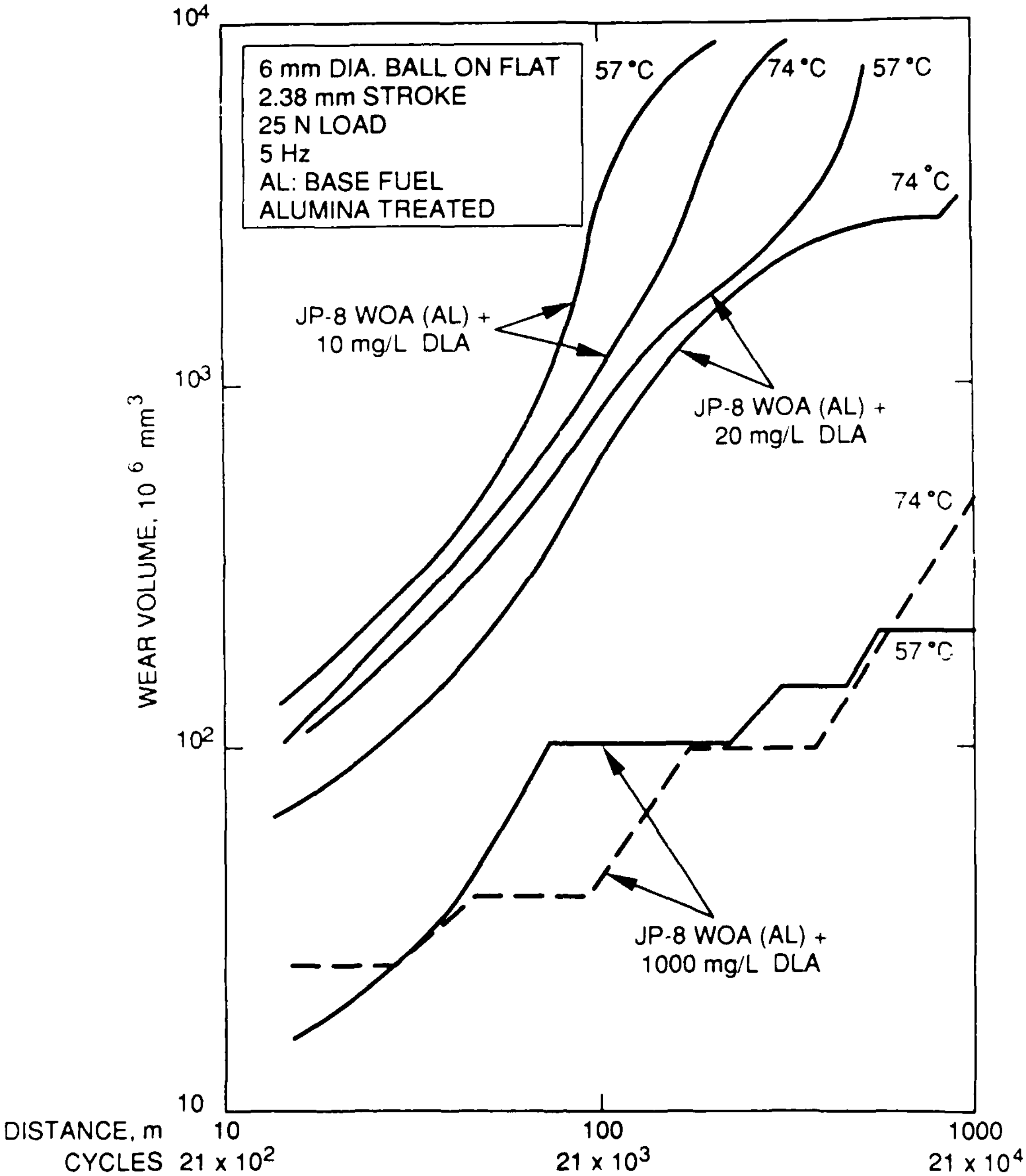

Figure 5. Effect of temperature on wear at various additive concentrations

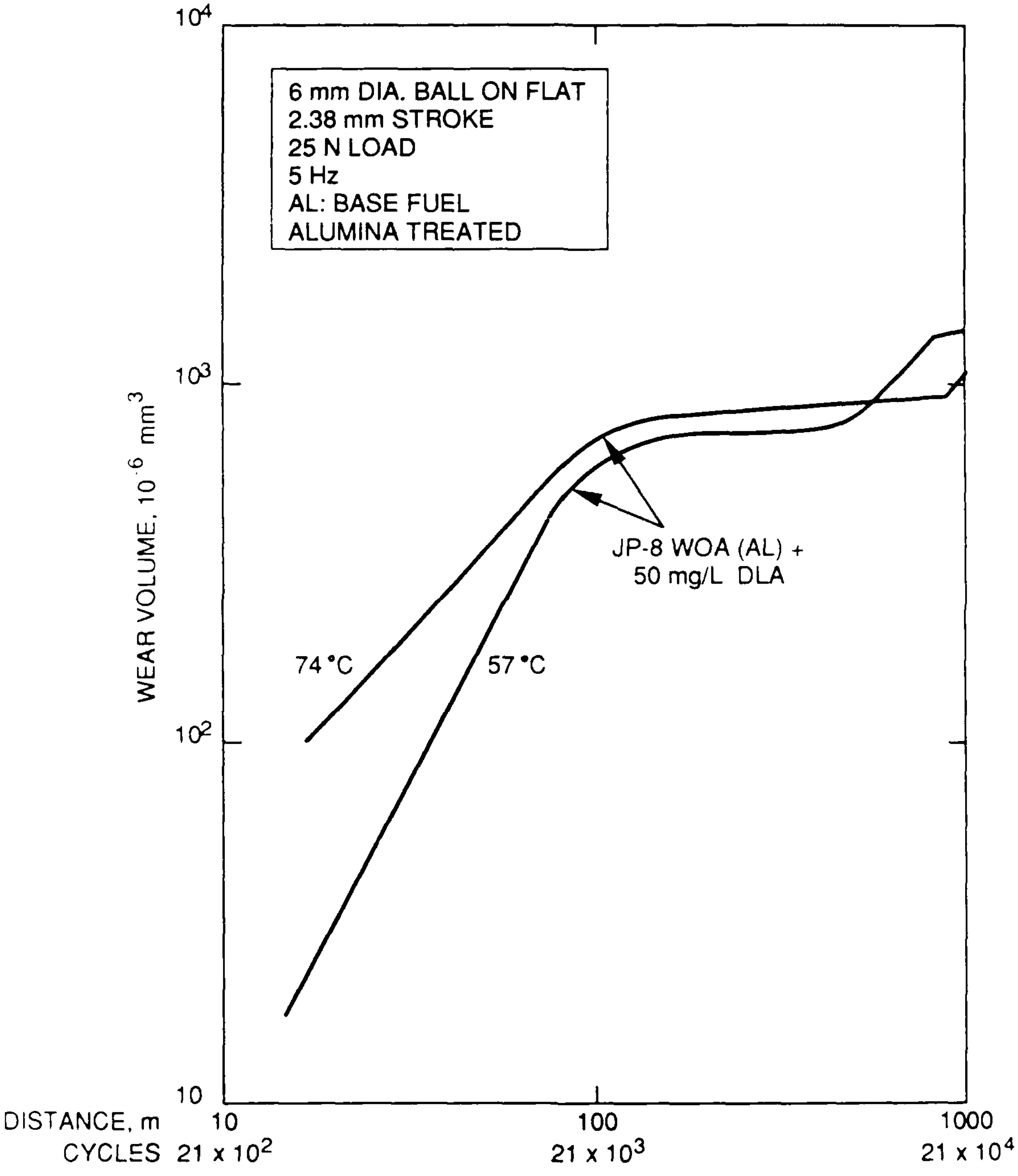

Figure 6. Effect of temperature on the wear at additive concentration of 50 mg/L DLA

It is of interest to note that the current range in treatment level for DLA-based corrosion inhibitor additives used in JP-8 is 9 to 31.5 mg/L as specified in MIL-I-25017D Qualified Products List (QPL-25017-15). Further, if it is reasonable to assume that 50 percent of the additive treatment level is an active ingredient, then a range of 4.5 to 16 mg/L DLA concentration could be found in current JP-8 fuels. This range is in contrast with the 10 to 1000 mg/L DLA concentration range used in the current study.

Fig. 7 is a simplified illustration of the qualitative behavior of wear with varying additive concentration. At temperature T_1, the adhesive wear decreases with increasing concentration of the additive. The progressively higher reaction rates of the additive with the surface reduce the rates of metallic asperity contacts and thus lower the adhesive wear. Beyond the optimum concentration at a given temperature, the wear mechanism changes to corrosive, and the wear begins to increase with the concentration. At higher temperatures ($T_2 > T_1$), the adhesive wear protection is provided at lower concentration of the additive and the optimum point shifts to the left. The reaction rates are higher at T_2; therefore, the whole curve shifts towards lower concentration. As shown in Fig. 7, the point of intersection of the two curves determines the concentration at which the wear behavior reverses with the temperature. At concentrations below the intersection, the wear is lower at the upper temperature; at concentrations above the intersection, the wear is lower at the lower temperature.

There are insufficient data in the current study to properly define the simplified wear relationships shown in Fig. 7. However, it is speculated that most of the wear data generated in the current study fall within the adhesive wear regime. It was not confirmed that the wear points using 1000 mg/L DLA fall within the corrosive wear mode. The concept of using optimal additive concentration/surface reactivity to minimize sliding wear has been reported by other investigators in the study of engine oil lubrication.(13,14)

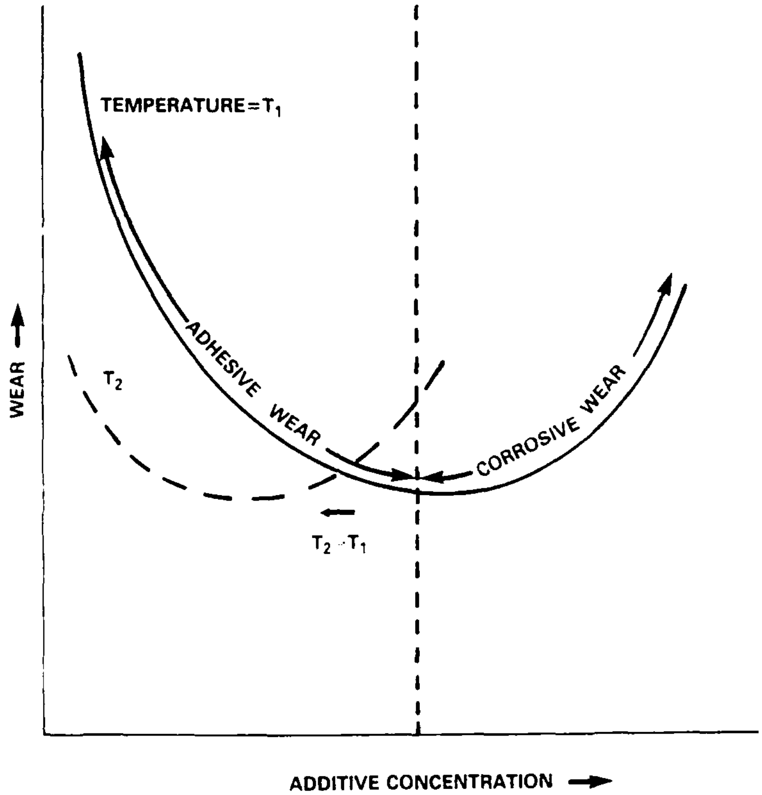

Figure 7. Qualitative relationship between additive concentration, temperature, and wear

V. SUMMARY/CONCLUSIONS

The objectives of this program were to evaluate fuel component wear protection characteristics of JP-8 when used in diesel-powered ground equipment and to develop methodology for determining the effects of lubricity additives on the low-viscosity fuels.

The tests conducted in this program suggest that the chemical composition of the fuel is very important in determining its lubricity or wear reduction properties. The bench wear tests to date consistently discriminate between fuel types, fuels at different temperatures, and additive effects. In all cases, the wear rates of jet fuels or isoparaffinic solvents were improved by the addition of corrosion inhibitor or antiwear additives to match the lower wear rates of the

diesel fuels. However, pass/fail criteria for JP-8 or diesel fuel relating to the real hardware are not available at present. The field data on real fuel system components such as the Stanadyne DB2 distributor pump for the 6.2L diesel engine will define its wear life with various chemically characterized fuels. The test methodology from these studies can be used as a screening tool to find additives for enhancement of JP-8 lubricity. The test can also be used to ascertain minimum lubricity level for ground-powered diesel equipment if these requirements are found to be different from aviation JP-8 specification requirements.

VI. RECOMMENDATIONS

Until long-term fuel injection system wear-related data become available from field-operated equipment, no further laboratory wear studies are recommended. If long-term field data indicate cause for concern, then the laboratory test methodology developed in this program should be considered for defining supplemental additive treatment of JP-8-type fuels.

The criteria for minimum mechanical performance of questionable fuel injection system component(s) should be developed, and the critical element to be simulated should be identified. A bench test procedure such as described in this program can then be used to correlate the specimen wear to the critical component wear criteria.

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